Charm decays Within the Standard Model And beyond

Marina Artuso
Syracuse University

PANIC 2005, Santa Fe, New Mexico, October 26, 2005

Prologue: the beauty of charm

- Its discovery provided an important validation of the Standard Model.
- Its mass scale makes it an ideal laboratory to probe QCD in the non-perturbative domain.
- The study of its decays probes the CKM sector of the Standard Model
    - Directly (V_{cs}, V_{cd})
    - Indirectly, improving our knowledge of the hadronic matrix elements affecting B decays
- Charm decays provide a unique window on new physics affecting the u-quark-type dynamics.

Quark Mixing

- Weak interaction couples weak eigenstates, not mass eigenstates: CKM matrix relates these two

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta\left(1-\frac{1}{2}\lambda^2\right)\right) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2\left(1+i\eta\lambda^2\right) \\ A\lambda^2\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix}$$

weak eigenstates

V_{CKM}

mass eigenstates

Wolfenstein parameterization

To λ^3 in real part & λ^5 in im. part

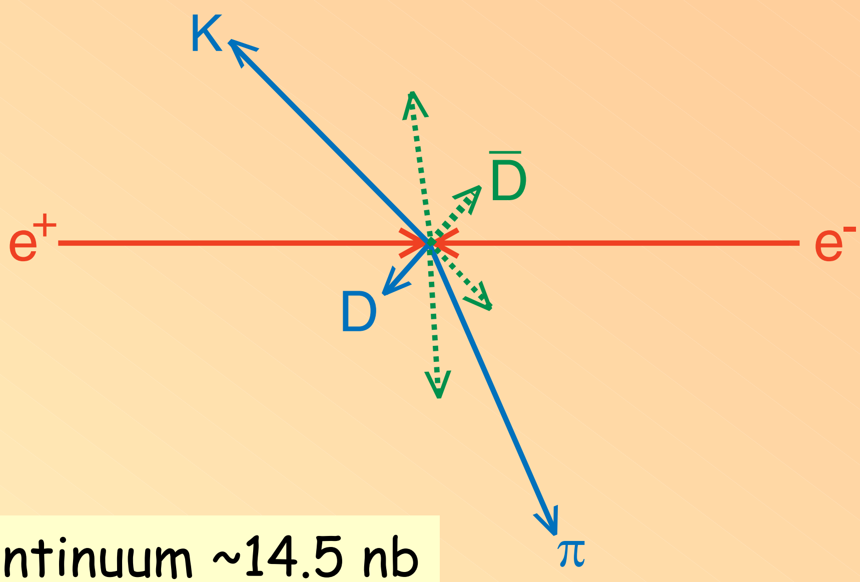
CKM unitary → described by 4 parameters (3 real, 1 imaginary: e.g. A,λ,ρ,η)

Experimental methods

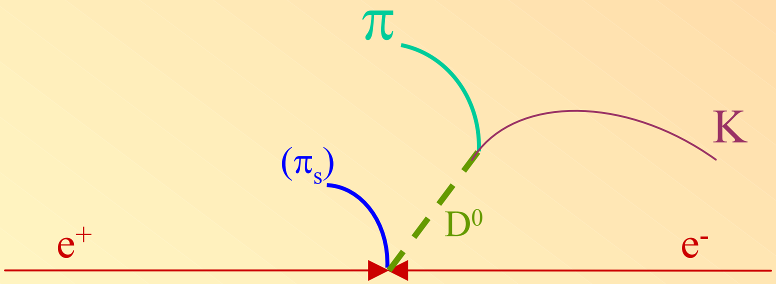
- $D\bar{D}$ production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.
    - Unique event properties
        - Only $D\bar{D}$ not $D\bar{D}x$ produced
    - Large cross sections:

$\sigma(D^0\bar{D}^0) =$ 3.72±0.09 nb
$\sigma(D^+D^-) =$ 2.82±0.09 nb
World Ave

    - Ease of $\mathcal{B}$ measurements using "double tags"
- B-factories (e^+e^-) + fixed target & collider experiments at hadron machines
    - D displaced vertex
    - $D^{*+} \rightarrow \pi^+ D^0$ tag



Continuum ~14.5 nb



Theoretical Tools

In order to extract fundamental Standard Model parameters we need to relate the world of hadrons to the world of quarks. The theoretical tools available are:

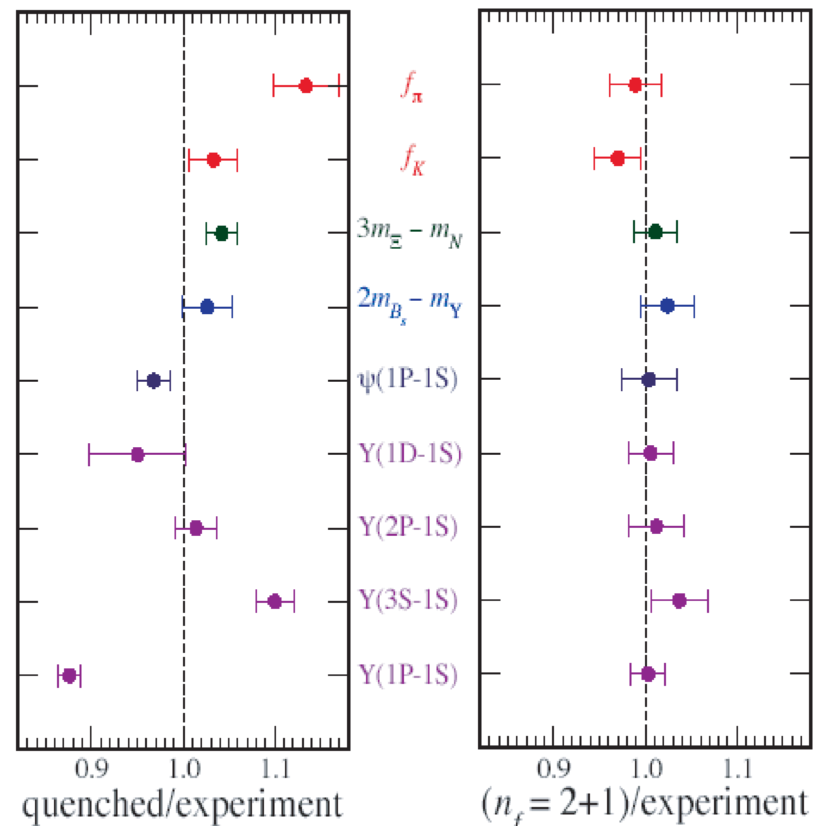
1. Lattice QCD: Theory (unquenched), still has moderate systematic errors; however theoretical accuracy can be improved in a controlled fashion.
2. QCD Sum Rules:
   - **Relationship between phenomenological and theoretical spectral functions;**
   - **Theoretical spectral functions are calculated from two or three-point correlators in perturbative QCD, including corrections from the OPE**
   - Many parameters, difficult to improve their accuracy in a systematic fashion.
3. Phenomenological models

   Important contributions to our understanding of charm decays; no way to improve these predictions in any systematic way

Predictive lattice QCD

- The foundations: unquenched lattice QCD demonstrated that it can reproduce several "golden properties"
- Predictive lattice QCD:
  - **f_D**
  - **Semileptonic D decay form factors**
  - **$M(B_c)$**

Davies et al., hep-lat/0304004



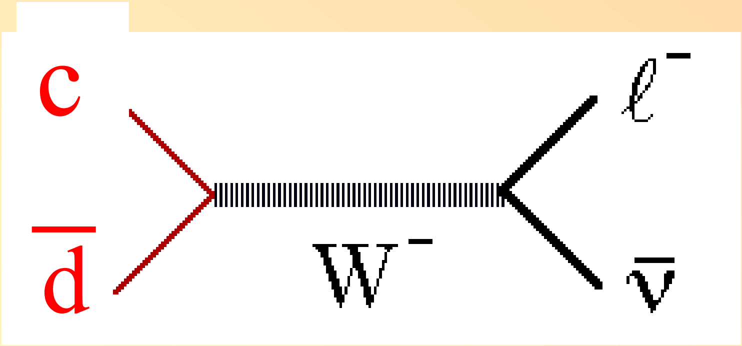
unquenched

Update: Ω^- works too!

Leptonic Decays: $D^+ \to \ell^+ \nu$

c and $\bar{d}$ can annihilate

probability is $\propto$ to wave function overlap



$$\Gamma(D^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_D^2 m_\ell^2 M_D \left(1 - \frac{m_\ell^2}{M_D^2}\right)^2 |V_{cd}|^2$$

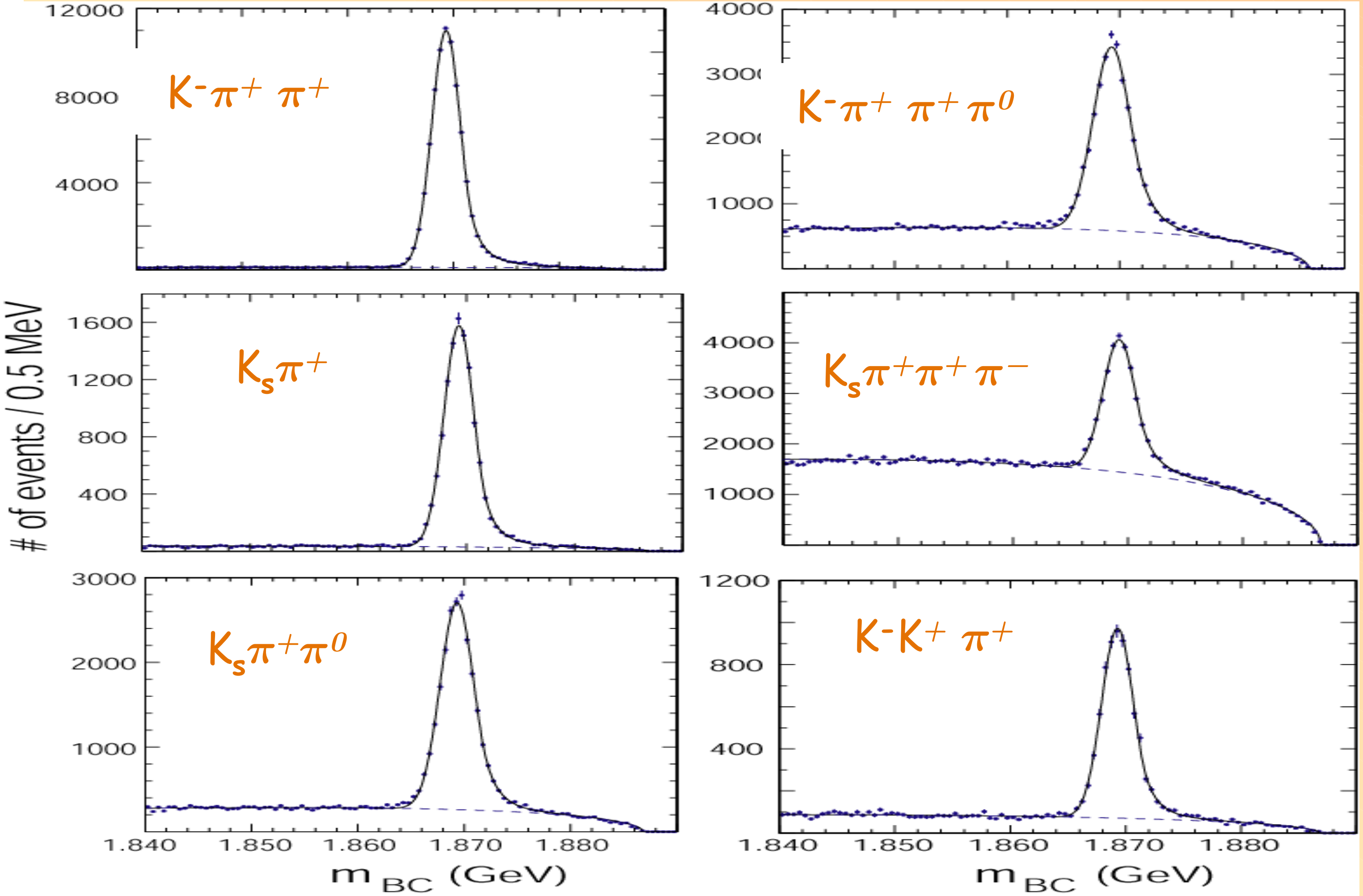
$d \to s$ $V_{cd} \to V_{cs}$ same process in the D_s system ($f_{D_s^+}$)

The importance of measuring the decay constants f_{D^+} and f_{D_s}

- We can compare theoretical calculations of f_D to experimental data and gain confidence in theory's ability to predict f_B
  - f_B is necessary to translate of B^o-$\bar{B}^o$ mixing data into $|V_{td}|$ thus constraining $\rho-\eta$
  - $f_{D^+}/f_{D_s^+}$ checks calculations of f_B/f_{B_s}
- Measurement of f_D & semileptonic form factors provide a check on theory independent of V_{cd} and V_{cs}

$$\frac{1}{\Gamma\left(D^+ \to \ell\nu\right)}\frac{d\Gamma\left(D^+ \to \pi e\nu\right)}{dq^2}\ \alpha\ \frac{P_\pi^3\left|f_+(q^2)\right|^2}{f_{D^+}^2}$$

New f_{D^+} measurement from CLEO-c



# of tags = 158,354±496, includes charge-conjugate modes

f_{D^+} measurement technique

- CLEO-c uses a sample tagged by D^+ hadronic decays (281 pb^{-1} to search for $D^+ \to \mu^+ \nu$)
- Use neutrino MM^2 observable to discriminate between signal and background:

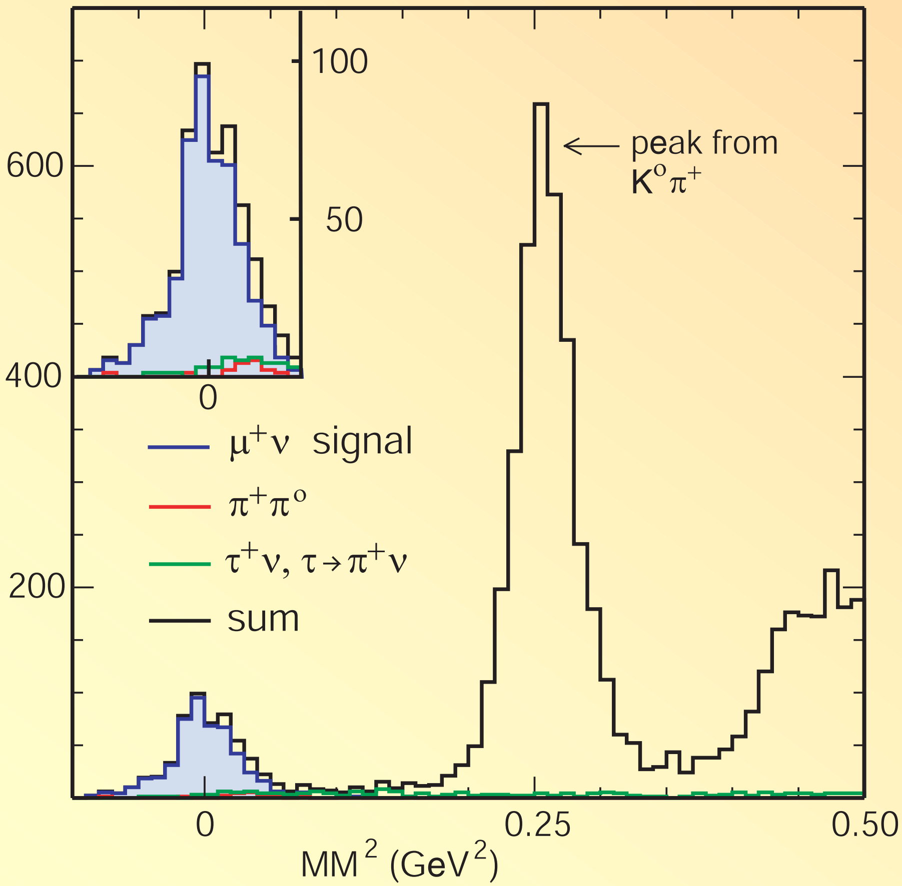
$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P_{D^-}} - \overrightarrow{P_\mu})^2$$

- Signal peaks at $MM^2 = 0$
- Additional cuts to suppress background:
  - No additional charged tracks from event vertex
  - Largest unmatched shower energy less than 0.25 GeV, to suppress $\pi^+\pi^o$
  - Muon candidate consistent with minimum ionizing particle (E_{cal}< 300 MeV in EM cal)
- Systematic errors are all determined using ***DATA***
- Detailed background studies based on *MC+* ***DATA***

$\Big\}$ Systematic errors are small and well understood

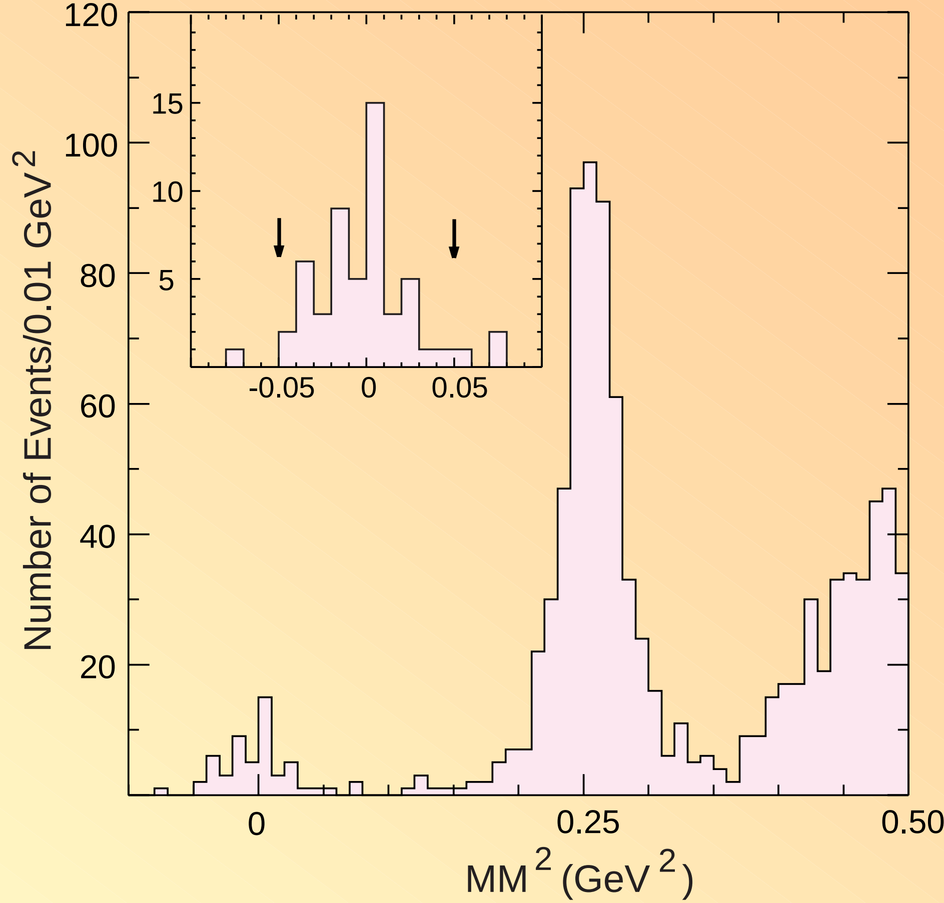
The $D^+ \to \mu^+\nu$ signal

MC Expectations from 1.7 fb^{-1}, 30 X data



281 pb^{-1} data set

50 events



Deriving a Value for f_{D^+}

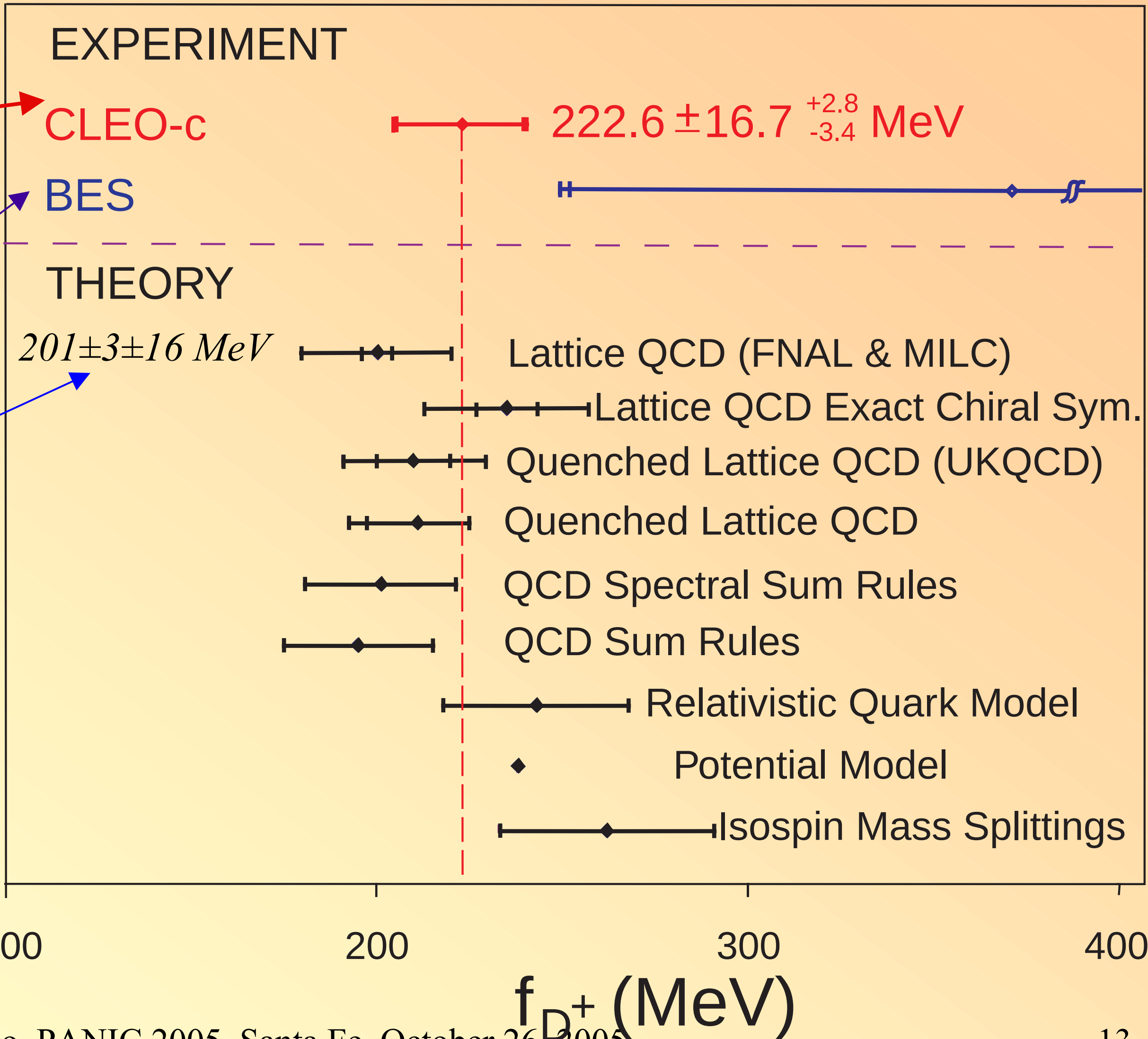
Backgrounds		
Mode	$\mathcal{B}$(%)	# Events
$\pi^+\pi^0$	0.13±0.02	1.40±0.18±0.22
$K^0\pi^+$	2.77±0.18	0.33±0.19±0.02
$\tau^+\nu$ ($\tau\rightarrow\pi^+\nu$)	2.65*$\mathcal{B}(D^+\rightarrow\mu^+\nu)$	1.08±0.15±0.16
Other D^+, D^o		<0.4, <0.4 @ 90% c.l.
Continuum		<1.2 @ 90% c.l.
Total		$2.81\pm0.30^{+0.84}_{-0.27}$

- $\mathcal{B}(D^+\rightarrow\mu^+\nu) = (4.40\pm0.66^{+0.09}_{-0.12})\text{x}10^{-4}$
- $f_{D^+} = (222.6\pm16.7^{+2.3}_{-3.4})$ MeV
- $\mathcal{B}(D^+\rightarrow e^+\nu) < 2.4\text{x}10^{-5}$ @ 90% c.l., rules out some non-Standard model theories

Efficiencies: μ^+ detection (69.4%); extra shower (96.1%); correction for easier tag reconstruction in $\mu^+\nu$ events (1.5%)

Comparison with Theory

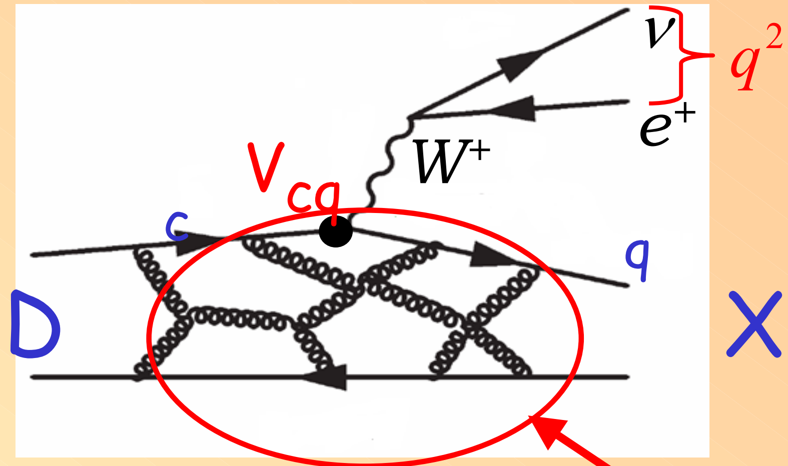
- CLEO-c new measurement
- BES measurement based on 2.67±1.74 events
- New Fermilab-MILC result
- Current Lattice measurement (unquenched light flavors) is consistent at 37% cl with CLEO-c result



Semileptonic Decays: $D \to X\ell^+\nu$

$$q^2 = \left(p_D^\mu - p_{hadron}^\mu\right)^2 = m_D^2 + m_P^2 - 2E_P m_D$$

- In principle, the best way to determine several magnitudes of CKM elements, is to use semileptonic decays. Decay rate $\alpha|V_{cq}|^2$
- This is how V_{us} and V_{cb} have been determined



Strong interaction effects

- Measure:

$$\frac{d\Gamma\left(D^+ \to Xe\nu\right)}{dq^2} = \frac{G_F^2}{24\pi^3} P_X^3 \left|f_+(q^2)\right|^2$$

Goals in Semileptonic Decays

- Assuming V_{cs} and V_{cd} known:
  - $D \to K(K^*)\ell\nu$ determine form factor shapes & distinguish among models + test lattice QCD predictions
  - $D \to \pi \to \ell\nu$
- Lattice checks comparing semileptonic ff & f_D
- Assuming lattice predictions OK:
  - measurements of V_{cd} & V_{cs} (+ V_{cb} would provide an important unitarity check)
  - V_{ub} use $D \to \rho\ell\nu$ to get form-factor for $B \to \rho\ell\nu$, at same v•v point using HQET (& $\pi\ell\nu$)

    Ligeti-Wise PRD53,4947(1996)
    Grinstein-Pirjol PLB533,8(2002)

Exclusive semileptonic decays from $\psi(3770)$ data

Recent data from CLEO-c and BES-II, use the kinematic variable

$$U \equiv E_{miss} - \left|\vec{p}_{miss}\right|$$

to select a specific semileptonic channel

CLEO-c (57 pb^{-1})

- $D^- \to K^+ \pi^- \pi^-$
- $D^- \to K_s \pi^-$
- $D^- \to K^+ \pi^- \pi^0$
- $D^- \to K^+ \pi^- \pi^- \pi^0$
- $D^- \to K_s \pi^- \pi^- \pi^+$

- $D^0 \to K^- \pi^+$
- $D^0 \to K^- \pi^+ \pi^0$
- $D^0 \to K^- \pi^+ \pi^- \pi^+$
- $D^0 \to K_s \pi^- \pi^+ \pi^0$
- $D^0 \to K^- \pi^+ \pi^0 \pi^0$
- $D^0 \to K_s \pi^0$
- $D^0 \to K^- K^+$

BES-II (33 pb^{-1})

$D^- \to K^+ \pi^- \pi^-$

$D^- \to K_s \pi^-$

$D^- \to K^+ \pi^- \pi^- \pi^0$

$D^- \to K_s \pi^- \pi^- \pi^+$

$D^- \to K^+ K^- \pi^-$,

$D^- \to K^+ \pi^+ \pi^- \pi^- \pi^-$

$D^0 \to K_s K^-$

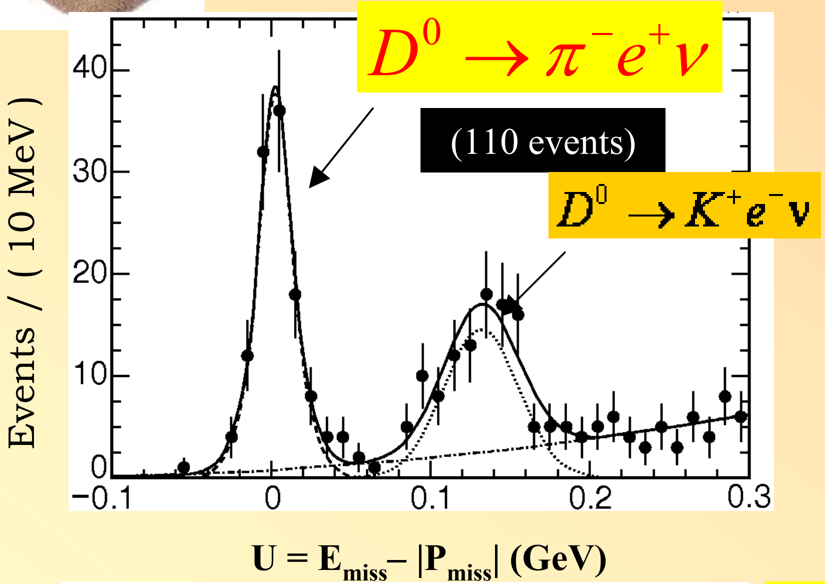
$D^0 \to K^+ \pi^+ \pi^- \pi^- \pi^-$

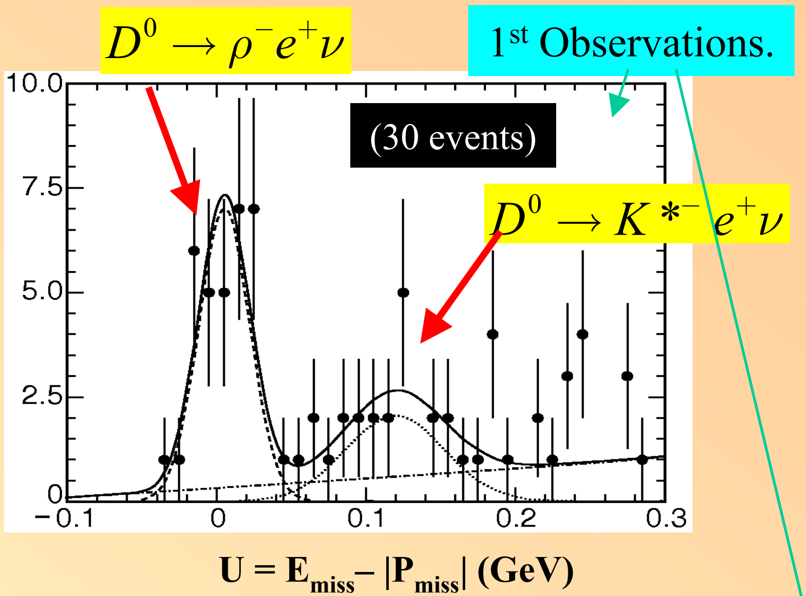
$D^0 \to K_s \pi^+ \pi^-$

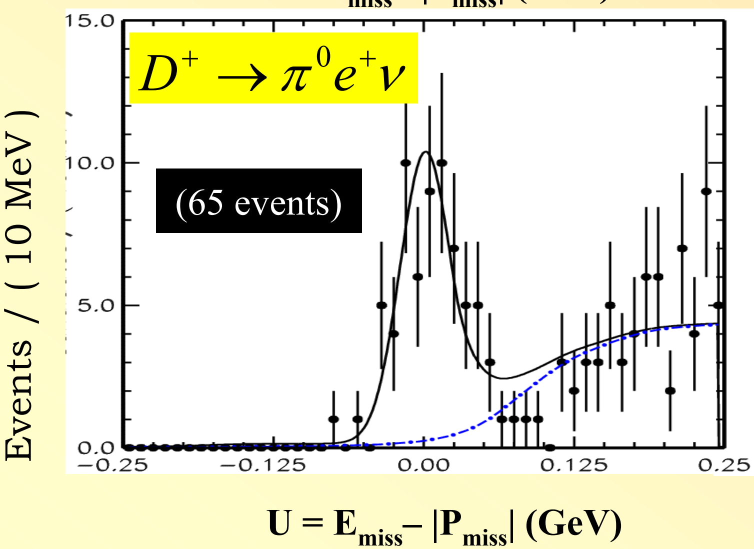
$D^0 \to K^+ \pi^- \pi^0$

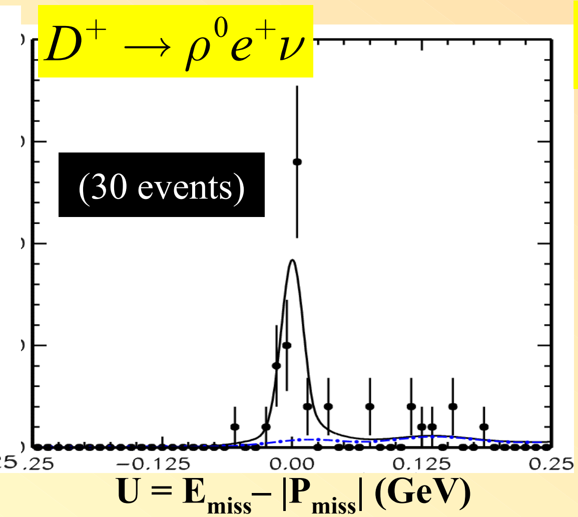
Tagging modes

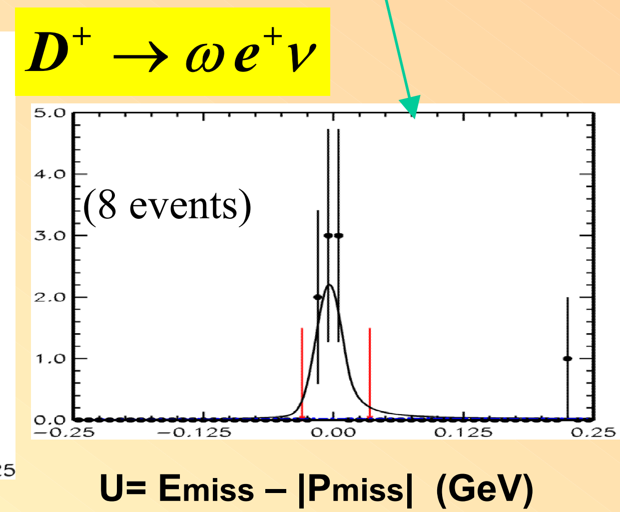
Cabibbo Suppressed Semileptonic Decays
CLEO-c









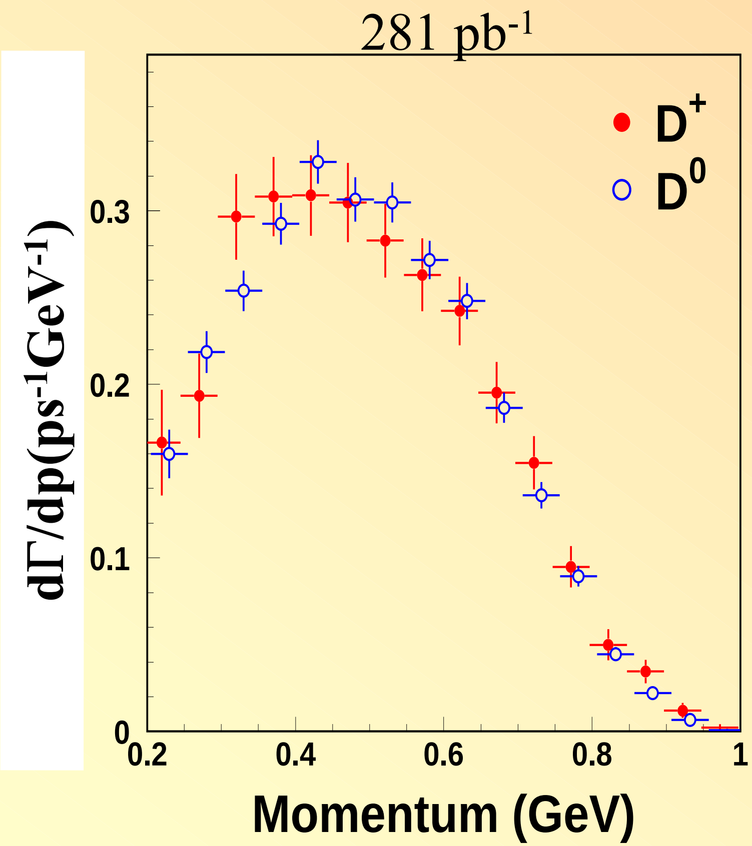


Exclusive branching fractions

First measurements by CLEO-c

Decay Mode	$\mathcal{B}$(%) (CLEO-c)	$\mathcal{B}$(%) (BES-II)	$\mathcal{B}$(%) (my ave including others)
$D^0 \to K^- e^+ \nu_e$	$3.44 \pm 0.10 \pm 0.10$	$3.82 \pm 0.40 \pm 0.27$	3.54 ± 0.11
$D^0 \to \pi^- e^+ \nu_e$	$0.262 \pm 0.025 \pm 0.008$	$0.33 \pm 0.13 \pm 0.03$	0.285 ± 0.018
$D^0 \to K^{*-} e^+ \nu_e$	$2.16 \pm 0.15 \pm 0.08$		2.14 ± 0.16
$D^0 \to \rho^- e^+ \nu_e$	$0.194 \pm 0.039 \pm 0.013$		
$D^+ \to \bar{K}^0 e^+ \nu_e$	$8.71 \pm 0.38 \pm 0.37$		8.31 ± 0.44
$D^+ \to \pi^0 e^+ \nu_e$	$0.44 \pm 0.06 \pm 0.03$		0.43 ± 0.06
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	$5.56 \pm 0.27 \pm 0.23$		5.61 ± 0.32
$D^+ \to \rho^0 e^+ \nu_e$	$0.21 \pm 0.04 \pm 0.01$		0.22 ± 0.04
$D^+ \to \omega^0 e^+ \nu_e$	$0.16^{+0.07}_{-0.01} \pm 0.01$		

Inclusive semileptonic branching fractions (preliminary - CLEO-c)



Lab momentum spectrum – no FSR correction

$$B(D^+ \to Xe\nu) = (16.19 \pm 0.20 \pm 0.36)\%$$

$$\sum B(D^+ \to Xe\nu)_{excl} = (15.1 \pm 0.50 \pm 0.5)\%$$

$$B(D^0 \to Xe\nu) = (6.45 \pm 0.17 \pm 0.15)\%$$

$$\sum B(D^0 \to Xe\nu)_{excl} = (6.1 \pm 0.2 \pm 0.2)\%$$

Are the charged and neutral semileptonic widths equal?

Cleo-c incl

$$\frac{\Gamma(D^0 \to Xe^+\nu_e)}{\Gamma(D^+ \to Xe^+\nu_e)} = 1.01 \pm 0.03(stat) \pm 0.03(sys)$$

Cleo-c excl

$$\frac{\Gamma(D^0 \to K^-e^+\nu_e)}{\Gamma(D^+ \to \bar{K}^0e^+\nu_e)} = 1.00 \pm 0.05(stat) \pm 0.04(sys)$$

BES-II

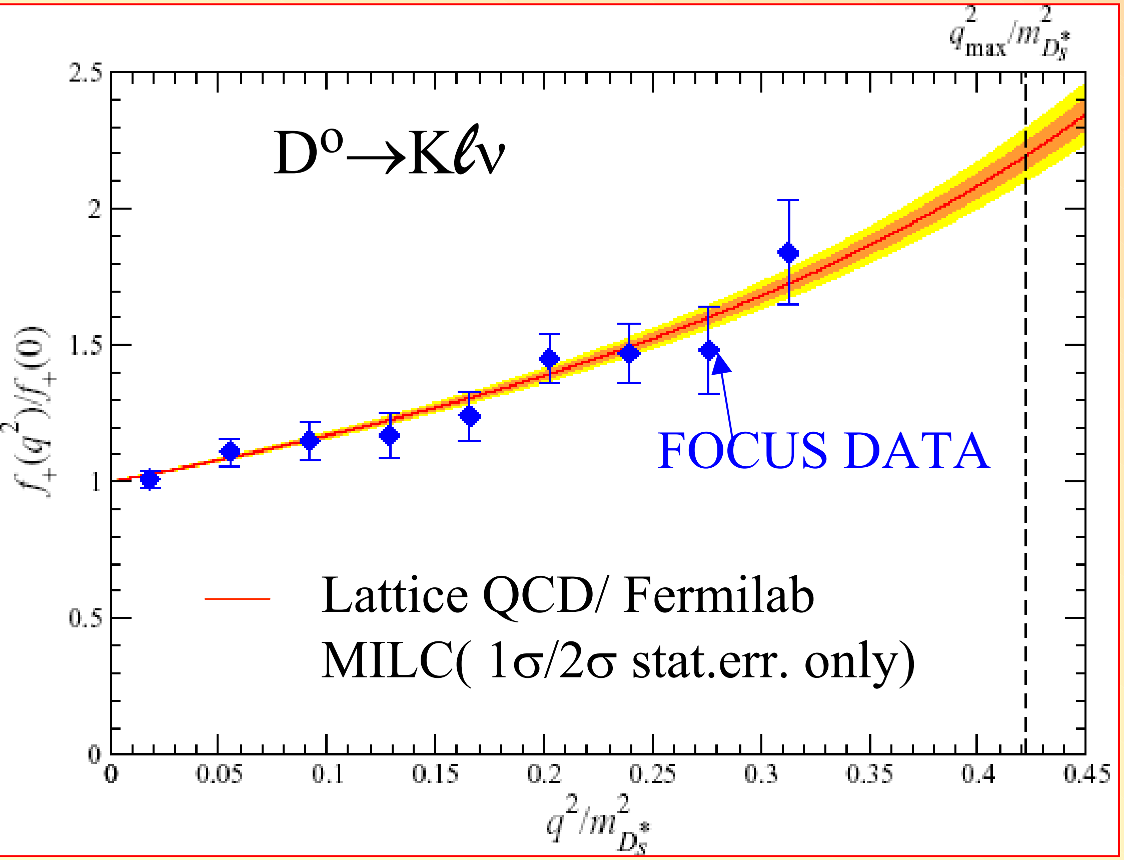
$$\frac{\Gamma(D^0 \to K^-e^+\nu_e)}{\Gamma(D^+ \to \bar{K}^0e^+\nu_e)} = 1.08 \pm 0.22(stat) \pm 0.07(sys)$$

Lattice comparison – the shape of $f^{+}(q^2)$

- Modern parameterization of the form factors proposed by Becirevic & Kaidalov (BK):

$$f^{+}(x) = f^{+}(0)\left(\frac{1}{1-q^2/m^2_{D_s^*}} - \underbrace{\frac{1}{1-\alpha q^2/m^2_{D_s^*}}}\right)$$

Representing contributions beyond the lowest lying resonances (D*)



Comprehensive analysis by Fajfer and Kamenik shows that including the next radial excitation in ff gives good fits to measured branching fractions.

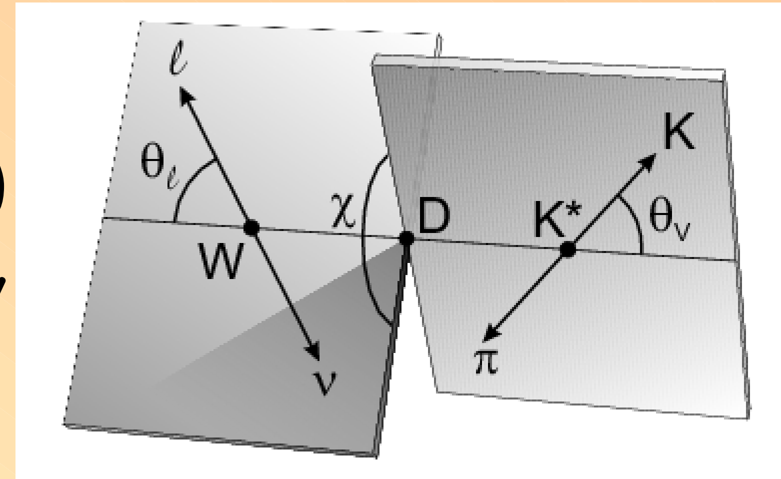
Fajfer et al. hep-ph/0506051 and 0412140

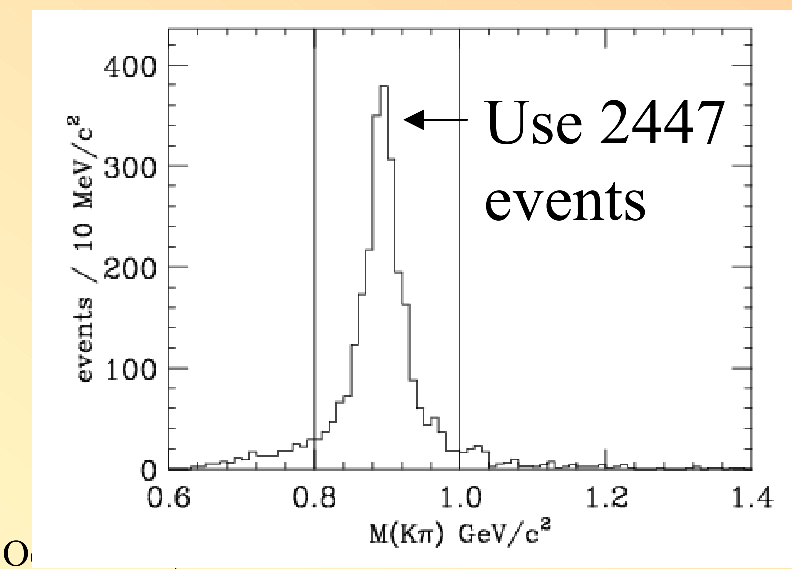
form factor shapes: what we know

$\alpha(D^o \to K\ell\nu)$	
Lattice (Fermilab-MILC hep-ph/0408306)	0.50±0.04(stat)
FOCUS	0.28 ±0.08 ±0.07
CLEO III	$0.36 \pm 0.10^{+0.03}_{-0.07}$
Belle	0.40 ±0.12 ±0.19
$\alpha(D^o \to \pi\ell\nu)$	
Lattice (Fermilab-MILC hep-ph/0408306)	0.44 ±0.04(stat)
CLEO III	$0.37\ ^{+0.20}_{-0.31} \pm 0.15$
Belle	0.03 ±0.27±0.13

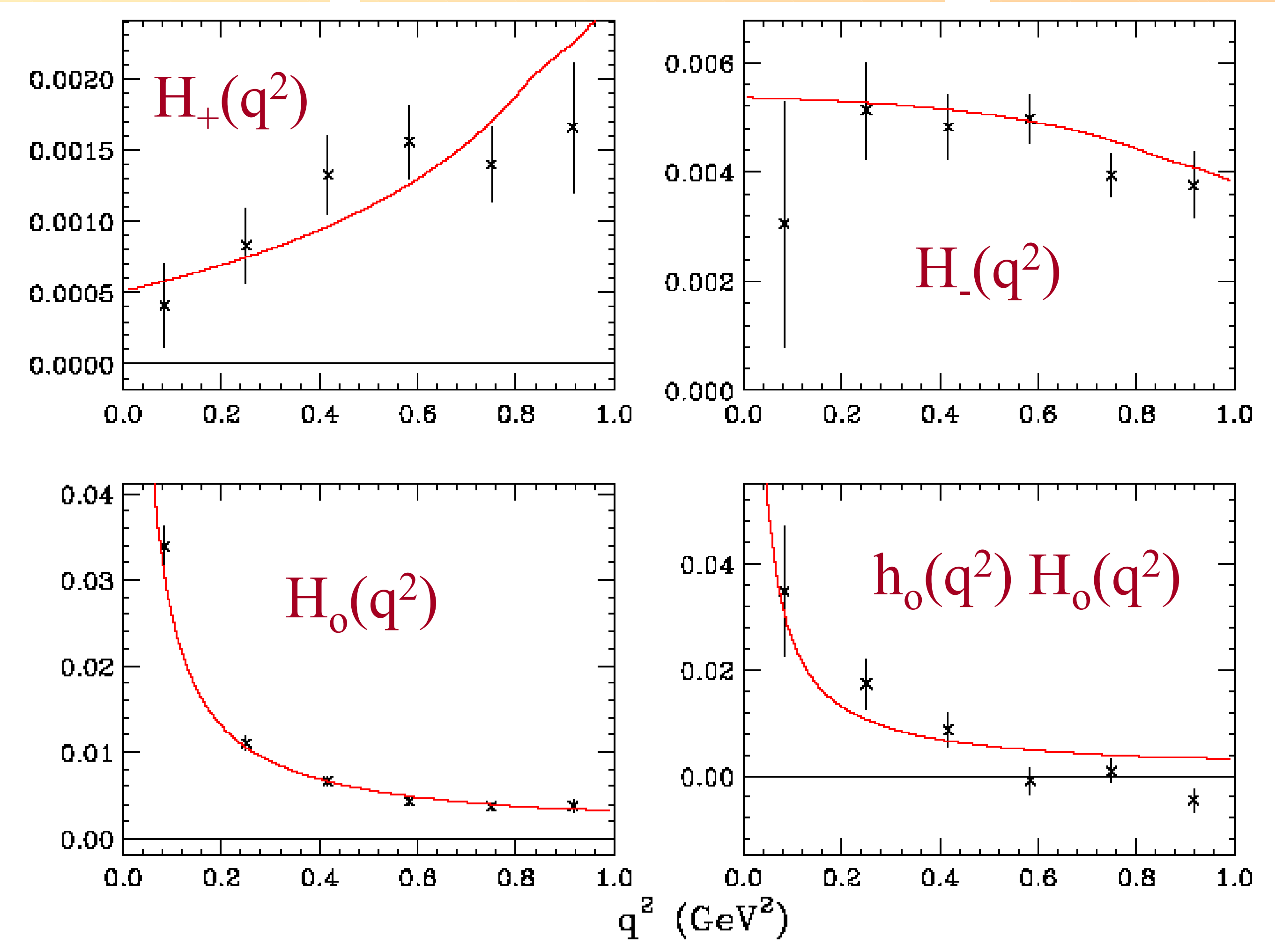
CLEO-c $D^+ \to K^- \pi^+ e^+ \nu$ Form Factors

- $K^- \pi^+$ mostly K^* with some s-wave (1st seen by FOCUS)
- For $D \to V e^+ \nu$, use 3 helicity amplitudes $H_o(q^2)$, $H_+(q^2)$, & $H_-(q^2)$
- Add $h_o(q^2) \cdot H_o(q^2)$ to account for s-wave term
- Use 281 pb^{-1}





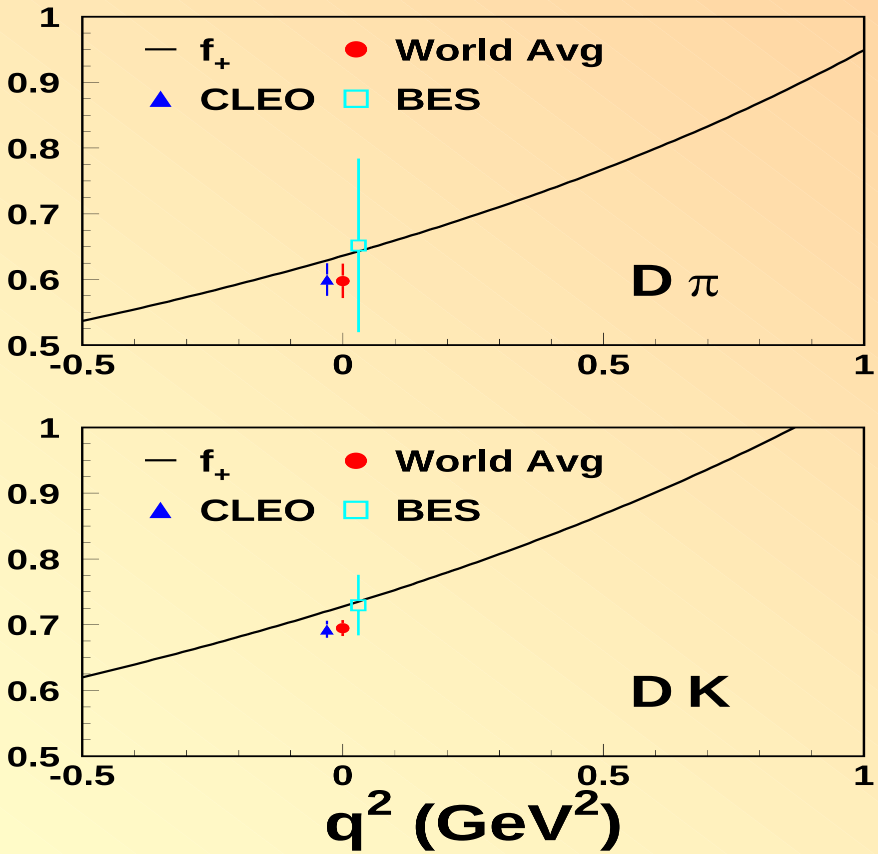
Form Factor Results (non-parametric analysis; CLEO-c)



- Significant s-wave amplitude confirmed
- $H_{+,-,0}$ helicity amplitudes
- h_o models s-wave component
- No evidence for d or f wave

Form factor normalization $f_+^K(0)$, $f_+^\pi(0)$

Cuves: FNAL-MILC hep-ph/0408306



If we assume that the lattice shape is OK ⇒ we can use measured branching fractions to validate the normalization

Lattice comparison: f_D and semileptonic form factors

- We can use a quantity independent of V_{cd} to do a CKM independent lattice check:

$$R_{\ell sl} \equiv \sqrt{\frac{\Gamma(D^+ \to \mu\upsilon)}{\Gamma(D \to \pi\ell\upsilon)}} \propto \frac{f_D}{f_+^\pi(0)}$$

- I obtain: $$R_{\ell sl}^{th} = 0.212 \pm 0.028$$

$$R_{\ell sl}^{\exp} = 0.249 \pm 0.022$$

- Theory and data consistent at 28% C.L.

The CKM Matrix

- Multifaceted unitarity checks
- Charm decays contribute:
  - With precision measurements of V_{cs} and V_{cd}, assuming that shape and normalization of the form factors are OK:

LEP W data 0.976±0.014, assuming unitarity hep-ex/0412015

$$V_{cs} = 0.957 \pm 0.017(\mathrm{exp}) \pm 0.093(\mathrm{th})$$

$$V_{cd} = 0.213 \pm 0.008(\mathrm{exp}) \pm 0.021(\mathrm{th})$$

$\nu,\bar{\nu}$ charm production off valence d quark 0.224±0.012 (PDG04 ave)

A rough unitarity check on on the second row:

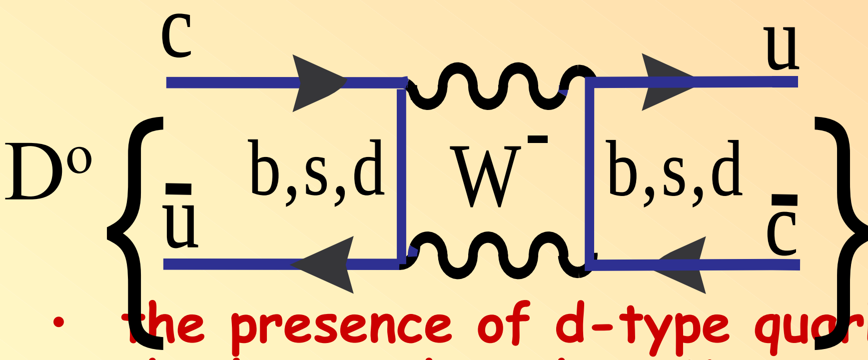
$$1-(V_{cd}^2+V_{cs}^2+V_{cb}^2)=0.037\pm0.181$$

Charm as a probe of new physics

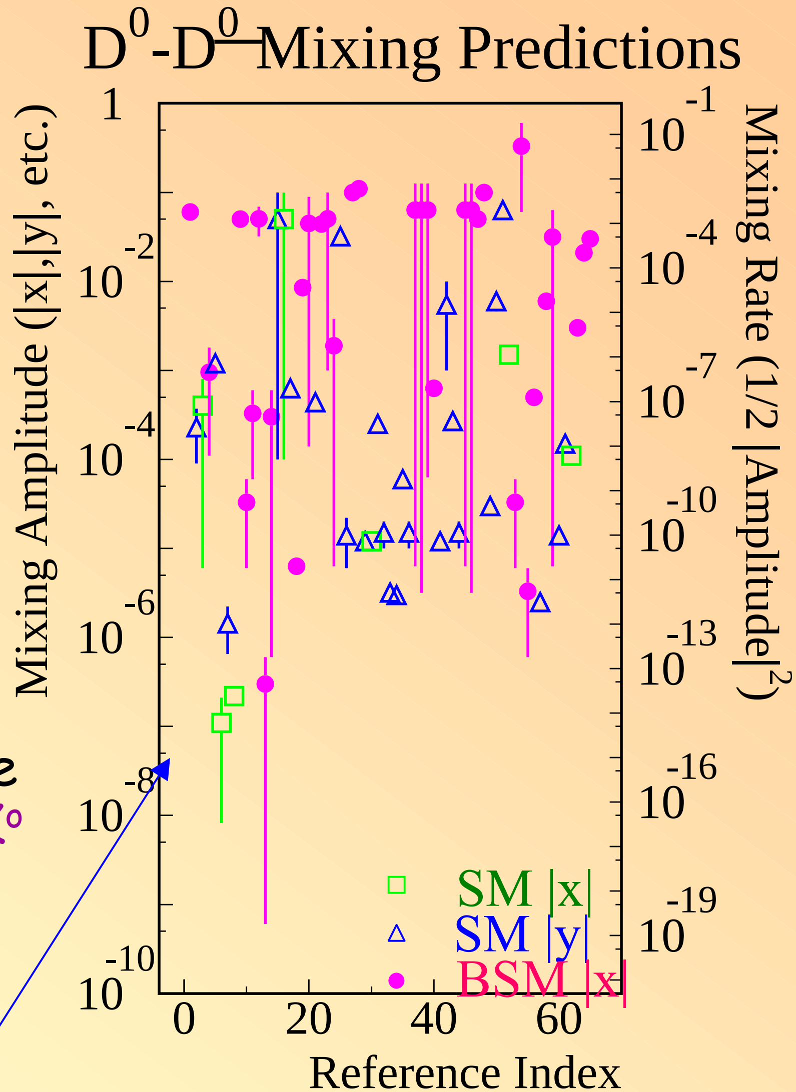
- Unique opportunities in three areas of investigation:
  - Mixing
  - CP violation
  - Rare decays
- Smoking gun or long distance effect?
  - Although all three phenomena suppressed in Standard Model, enhancement due to long distance effects may mimic new physics.

Case study I: mixing

- Mixing could proceed via



- **the presence of d-type quarks in the loop makes the SM expectations for D^o- $\bar{D}^o$ mixing small** compared with systems involving u-type quarks in the box diagram because these loops include 1 dominant super-heavy quark **(t)**: K^o (50%), B^o (20%) & B_s (50%)
- New physics in loops implies $x \equiv \Delta M/\Gamma >> y \equiv \Delta\Gamma /2\Gamma$; but long range effects complicate predictions



From H. Nelson

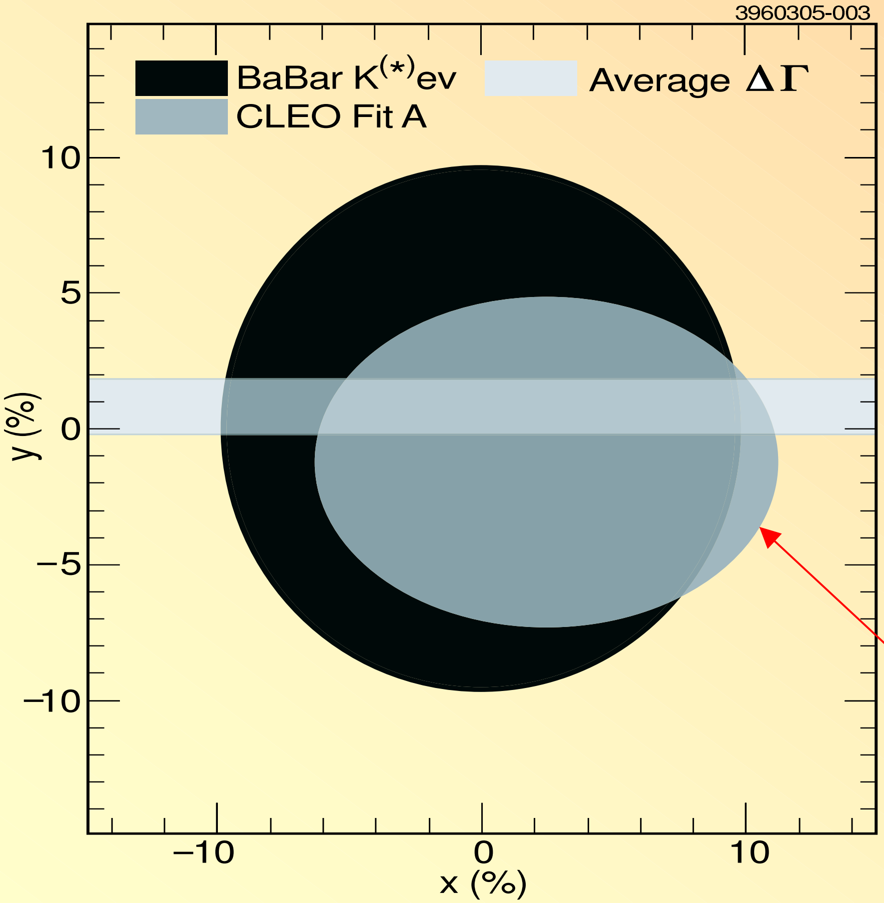
$D^0 \bar{D}^0$ mixing: the data

- The study of D^0 wrong-sign $K\pi$ yields has been a key step in our experimental study of D^0 D^0 mixing.
- Caveats:
  - Complicated by interference between DCSD & mixing [strong phase $\delta \Rightarrow$ data constrain only x' & y']
  - Complicated by CP violation

Experiment	x'^2 (95 % C.L.) ($\times 10^{-3}$)	Y'(95% C.L.) ($\times 10^{-3}$)
Belle (2004)	0.89	$-30 < Y' < 27$
BaBar (2003)	2.2	$-56 < Y' < 39$
FOCUS (2001)	1.52	$-124 < Y' < -5$
CLEO (2000)	0.82	$-58 < Y' < 10$

Most general fit

$D^0\ \bar{D}^0$ mixing: the data II



- D^0 semileptonic decays: $R_{ws} = \frac{1}{2}(x^2+y^2)$ [no strong phase δ]

Experiment	R_M(95% CL)	$\sqrt{x^2+y^2}$
BaBar 04	0.0046	0.1
Belle 05	0.0016	0.056
CLEO 05	0.0091	0.135

- Dalitz plot analysis of $D^0 \to K_s^0 \pi^+ \pi^-$ (CLEO II.V) comparable sensitivity

CP/T Violation

- Unexpectedly large CP violation asymmetries may be a better signature for new physics (0.01-0.001)
- CP violation can be studied in a variety of ways:
  - Direct CP violation
  - CP violation in mixing
  - T violation in 4-body decays of D^0/D^+ (assuming CPT) and studying triple product correlations
  - Exploiting quantum coherence of $D\overline{D}$ produced in $\psi(3770)$ decays

CP/T Violation: a sampler of recent data

Experiment	Decay mode	A_{CP} (%)	Notes
BaBar	$D^+ \to K^- K^+ \pi^+$	$1.4 \pm 1.0 \pm 0.8$	
BaBar	$D^+ \to \phi^+ \pi^+$	$0.2 \pm 1.5 \pm 0.6$	Res. Substr. Of $D^+ \to K^- K^+ \pi^+$
BaBar	$D^+ \to K^{*0} K^+$	$0.9 \pm 1.7 \pm 0.7$	
CLEO II.V	$D^0 \to \pi^+ \pi^- \pi^0$	$1^{+9}_{-7} \pm 8$	Dalitz plot analysis constraints also $\pi\,\pi$ s-wave component
FOCUS	$D^0 \to K^+ K^- \pi^+ \pi^-$	$1.0 \pm 5.7 \pm 3.7$	T violation through triple product correlations
FOCUS	$D^+ \to K^0_S K^+ \pi^+ \pi^-$	$2.3 \pm 6.2 \pm 2.2$	
FOCUS	$D_S \to K^0_S K^+ \pi^+ \pi^-$	$-3.6 \pm 6.7 \pm 2.3$	

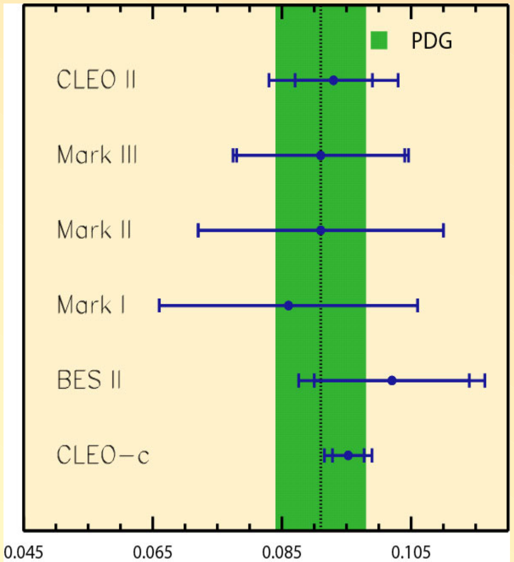
Epilogue: charm as a facet of beauty

- Charm improves b decay studies in several ways:
  - D absolute branching fractions $\Rightarrow$ B absolute branching fractions
  - Dalitz plot analyses $\rightarrow$ determination of the angle γ

D absolute branching fractions

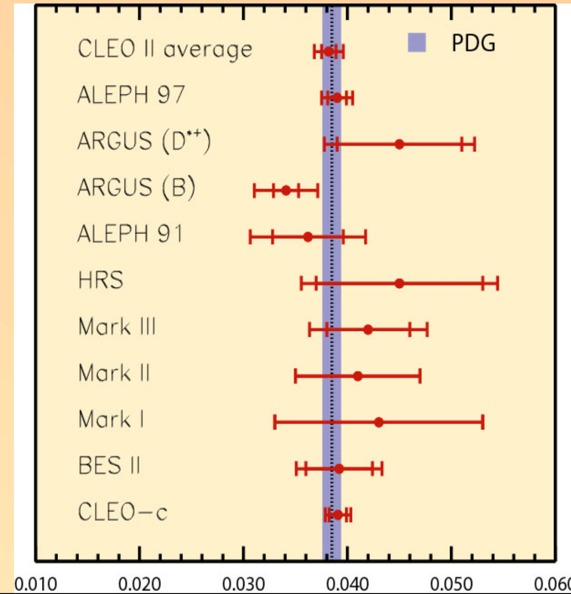
$\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)$

$\mathcal{B}(D^o \to K^- \pi^+)$



CLEO-c corrected for final state radiation (fsr), others not

Three best measurements

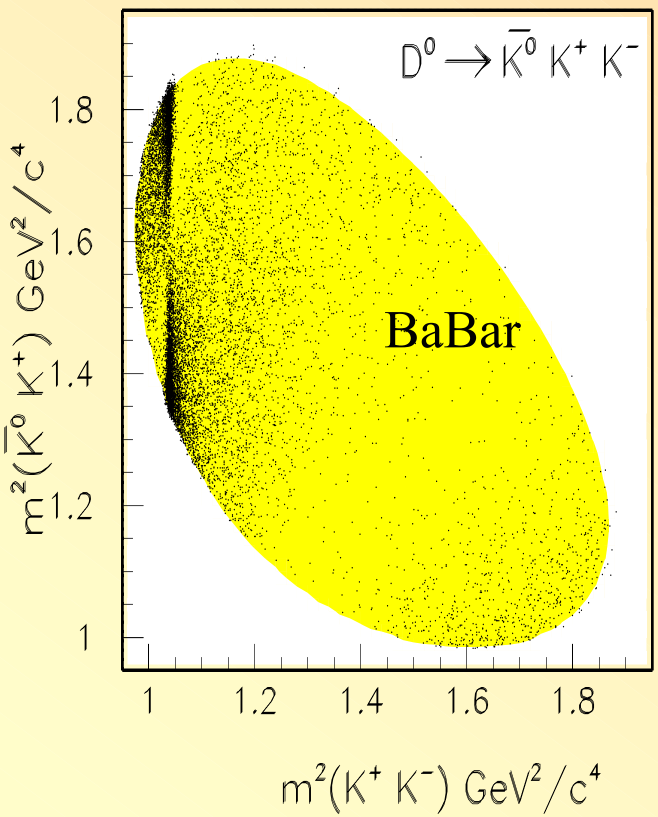


$\mathcal{B}$ (%)	Error(%)	Source
9.3±0.6±0.8	10.8	CLEO II
9.1±1.3±0.4	14.9	MK III
9.52 ±0.25±0.27	3.9	CLEO-c

$\mathcal{B}$ (%)	Error(%)	Source
3.82±0.07±0.12	3.6	CLEO II
3.90±0.09±0.12	3.8	ALEPH
3.91±0.08 ±0.09	3.1	CLEO-c

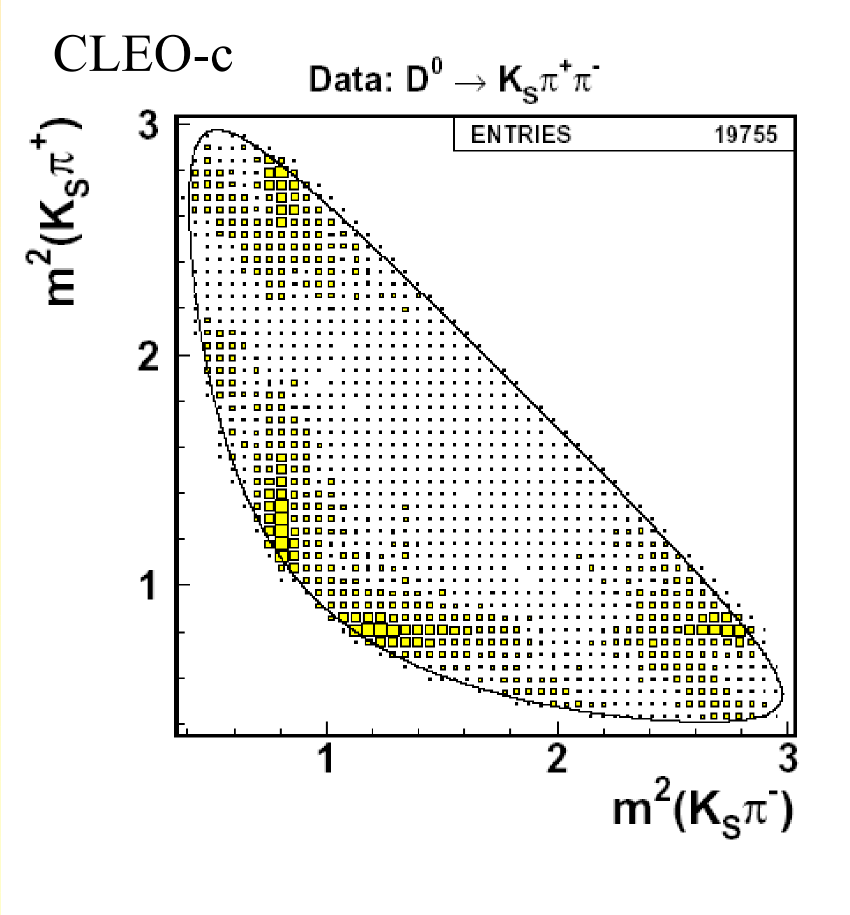
My averages: (9.51±0.34)% (3.92±0.08)%, both corrected for fsr

Dalitz plot studies



- Large fraction of the known D meson decay rate proceeds through 3 body hadronic decays involving π and K.
- These decays are dominated by quasi-2 body final states with a rich set of resonance.
- Their strength and interference patterns useful to understand light hadron spectroscopy.

Charm factories at threshold contribution



- Input to determination of CKM phase γ from $B \to D[K_s\pi^+\pi^-]K$
- Recent results from BaBar and Belle:

$$\phi_3 = (77^{+17}_{-19} \pm 13 \pm 11) \text{ deg}$$

$$\gamma = (70 \pm 26 \pm 10 \pm 10) \text{ deg}$$

Third error is model dependence of Dalitz plot fit: may be reduced by simultaneous fit to generic $K_s\pi\pi$ and CP tagged (CP even and odd) Dalitz plots.

Conclusions I

- Precision studies of charm and beauty decays are a crucial complement to energy frontier experiments **to develop a more complete understanding of fundamental particles and their interactions (new physics):**
  - The synergistic efforts of theorists and experimentalist will lead to a better understanding of QCD in the non-perturbative regime
    - ⇒Precision tests of the Standard Model
    - ⇒New tools applicable to other theoretical particle physics problems.

Conclusions II

- Large data samples at center-of-mass energies near $D\bar{D}$ (and $D_s\bar{D}_s$) threshold are providing unique constraints to the Standard Model and may uncover unique signatures of new physics.
- The study of charm and beauty decays at e^+e^- & hadron collider b-factories represent another facet of this rich program

The study of

charm

and

beauty

is a key element of the next generation of high energy physics experiments.